

Behavioural and Radio Frequency Characterization of Consumer-Grade UAV Control Systems Using Passive Sensing

Jonnadula Narasimharao, Vignesh Durishetty, G. Agratha Reddy, J. Swathi

Abstract - The rapid proliferation of consumer-grade Unmanned Aerial Vehicles (UAVs) has introduced significant concerns related to airspace security, privacy, and unauthorized surveillance. Traditional UAV detection techniques such as radar, vision-based systems, and acoustic sensing exhibit limitations in terms of cost, environmental dependency, and scalability. In this context, Radio Frequency (RF)-based monitoring has emerged as a practical alternative due to its ability to directly analyze communication signals between UAVs and their controllers.

This paper presents a passive RF sensing framework for the behavioural and communication characterization of consumer-grade UAV control systems. Unlike active detection systems, the proposed approach does not transmit or interfere with RF signals, ensuring a non-intrusive and legally compliant monitoring mechanism. A Software Defined Radio (SDR)-based system is employed to capture RF signals in the widely used 2.4 GHz frequency band. Signal processing techniques, including Fast Fourier Transform (FFT), Power Spectral Density (PSD) estimation, and Received Signal Strength Indicator (RSSI) analysis, are applied to extract meaningful communication features.

The system correlates RF signal characteristics with UAV operational states such as initialization, takeoff, hovering, movement, altitude variation, and landing. Experimental results demonstrate consistent behavioral patterns in signal strength, transmission bursts, and bandwidth occupancy corresponding to different flight phases. The findings indicate that passive RF sensing provides a low-cost, scalable, and effective solution for UAV behavioral analysis, making it suitable for security monitoring, restricted zone surveillance, and academic research applications.

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1. Introduction

The increasing use of consumer-grade Unmanned Aerial Vehicles (UAVs) has raised concerns regarding airspace safety, privacy, and security, particularly in wireless communication environments [2]. However, this rapid growth has also introduced serious concerns related to unauthorized airspace intrusion, privacy violations, and security threats in sensitive environments such as airports, military zones, and urban infrastructures. The need for reliable UAV detection and monitoring systems has therefore become a critical research area.

Traditional UAV detection approaches include radar-based systems, vision-based detection, and acoustic sensing techniques. While radar systems provide wide-area coverage, they are often expensive and ineffective for detecting small, low-altitude drones due to their low radar cross-section. Vision-based systems rely on cameras and deep learning models but suffer from environmental dependencies such as lighting conditions, weather, and line-of-sight limitations. Acoustic systems, although cost-effective, are constrained by limited range and sensitivity to environmental noise.

In contrast, RF-based detection systems leverage the communication link between the UAV and its controller. Since most consumer drones operate in unlicensed Industrial, Scientific, and Medical (ISM) bands such as 2.4 GHz and 5.8 GHz, monitoring RF signals provides a direct and reliable method for identifying drone activity. However, existing RF-based systems primarily focus on detecting the presence of UAVs rather than analyzing their communication behavior.

This paper addresses this limitation by proposing a passive RF-based framework that not only detects UAV communication but also characterizes behavioral patterns associated with different operational states. By analyzing signal strength variations, transmission patterns, and spectral characteristics, the system provides deeper insights into UAV activity beyond simple detection.

2. Literature Survey

Extensive research has been conducted in the domain of UAV detection using various sensing modalities. Radar-based systems have been widely used in military applications, with advanced techniques such as micro-Doppler analysis enabling detection of rotor blade signatures. However, their high cost, infrastructure requirements, and inefficiency in detecting small drones limit their applicability in civilian and academic environments. [1]

Vision-based detection systems utilize computer vision algorithms and deep learning

models such as Convolutional Neural Networks (CNNs) to identify drones in visual data. Although these systems achieve high accuracy under controlled conditions, their performance deteriorates significantly in adverse weather conditions, low lighting environments, and scenarios with visual obstructions.

Acoustic detection systems rely on analyzing sound signatures generated by drone motors and propellers. Techniques such as Fast Fourier Transform (FFT) are used to extract frequency components associated with UAV operation. While these systems are cost-effective, their reliability is compromised in noisy environments and their detection range is limited.

RF-based detection systems have gained significant attention due to their ability to monitor UAV communication directly [4], [7]. Early approaches utilized spectrum analyzers to detect signal anomalies, while recent advancements incorporate RF fingerprinting and machine learning techniques to classify drone signals [5]. However, these methods often require large datasets, high computational resources, and proprietary hardware, making them less accessible for academic research.

A key research gap identified in existing literature is the limited focus on behavioral characterization of UAV communication. Most systems are designed to answer whether a drone is present, rather than analyzing what the drone is doing. This work aims to bridge that gap by developing a passive RF sensing system capable of correlating signal characteristics with UAV operational behavior [6].

3. Proposed Methodology

The proposed system is designed as a passive RF sensing framework that captures and analyses communication signals between a UAV and its remote controller. The overall system architecture of the proposed passive RF sensing framework is illustrated in Fig. 1. The architecture consists of sequential modules including RF signal acquisition, preprocessing, feature extraction, behavioural correlation, and visualization, enabling structured analysis of UAV communication behaviour.

The system architecture consists of five major modules: RF signal acquisition, signal preprocessing, feature extraction, behavioural correlation, and data visualization.

The RF signal acquisition module utilizes a Software Defined Radio (SDR) to monitor

Drone RF Monitoring System

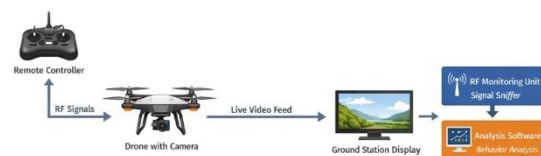


Fig. 1. Proposed passive RF-based UAV characterization system architecture

the 2.4 GHz frequency band [3], [9]. The SDR captures raw RF signals in the form of in-phase (I) and quadrature (Q) samples, enabling both time-domain and frequency-domain analysis. The captured signals are then processed to remove noise and isolate relevant communication components using band-pass filtering techniques [5].

Feature extraction is performed using signal processing algorithms such as FFT and PSD estimation. Key parameters including RSSI, bandwidth occupancy, transmission intervals, and frequency stability are computed. These features are analysed to identify communication patterns associated with UAV activity [6].

The behavioural correlation module maps extracted RF features to specific UAV operational states. Controlled flight experiments are conducted to observe signal variations during initialization, take-off, hovering, movement, and landing. By comparing feature values across different phases, the system establishes behavioural signatures corresponding to each operation

Finally, the results are visualized using graphical representations such as spectrum plots, signal strength graphs, and frequency heatmaps, enabling intuitive interpretation of UAV communication behaviour.

4. Experimental Setup

The experimental setup consists of a consumer-grade UAV, its remote controller, a Software Defined Radio (SDR), and a computing system for signal processing. The SDR is connected to a laptop via a USB interface and equipped with an antenna tuned to the 2.4 GHz frequency band , following widely adopted SDR- based RF monitoring configurations [8], [9].

As shown in Fig. 2. The Controlled flight experiments are conducted to capture RF signals during various UAV operational states. These include initialization, take-off, hovering, directional movement, altitude variation, and landing. The SDR continuously scans the frequency band and records RF data for both real-time and offline analysis.



Fig. 2. Test Flight version of the drone (UAV)

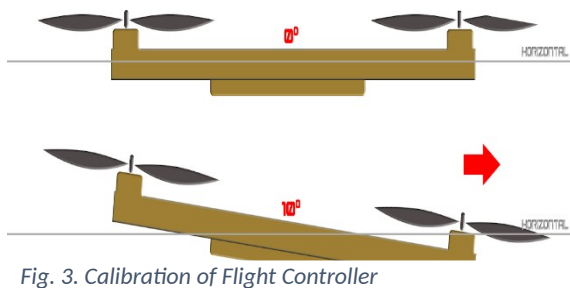


Fig. 3. Calibration of Flight Controller

To ensure consistency, experiments are performed under controlled environmental conditions with fixed antenna positioning and repeated flight patterns.

This allows reliable comparison of signal characteristics across multiple trials.

5. Results and Discussion

The experimental results demonstrate the effectiveness of the proposed passive RF sensing system in capturing and analysing UAV communication behaviour. Distinct RF signal patterns were observed corresponding to different operational states of the UAV. During initialization and pairing, unique signal spikes were detected, indicating the establishment of communication between the UAV and the controller.

During takeoff, noticeable fluctuations in RSSI were observed due to rapid positional changes. Hovering resulted in stable signal strength and periodic transmission bursts, reflecting steady communication. In contrast, directional movement and altitude variation introduced significant fluctuations in RSSI and increased transmission density [6].

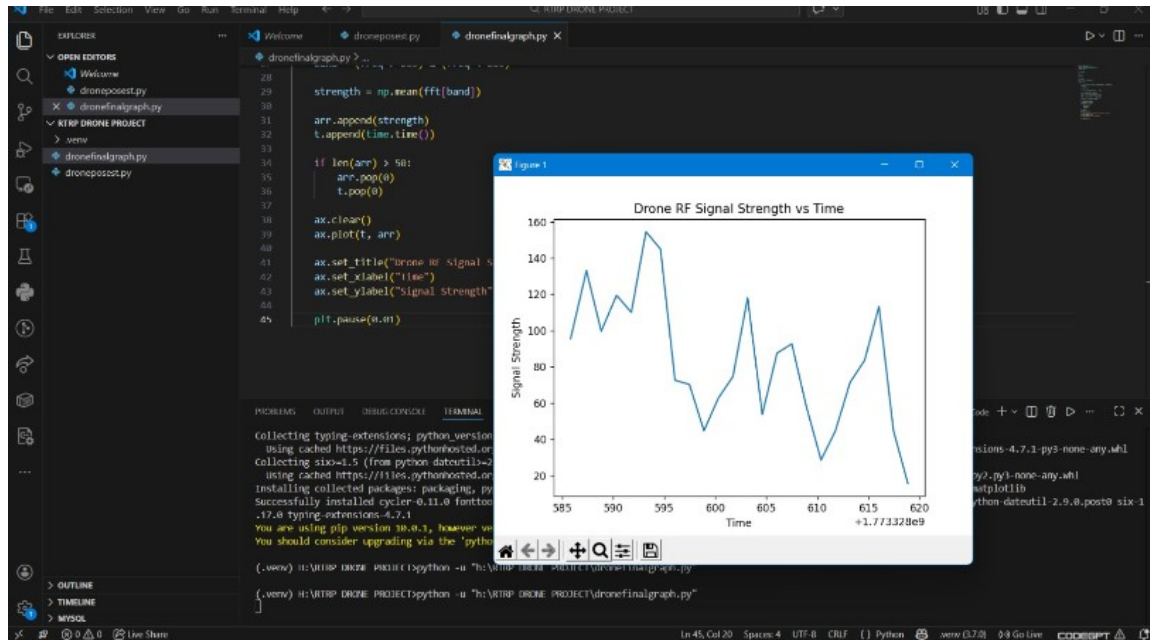


Fig. 4. RSSI variation during different UAV operational states

Bandwidth analysis revealed that UAV communication occupies a narrow frequency range within the monitored band, with slight variations during active control adjustments. Transmission burst analysis showed periodic communication patterns during stable flight and increased irregularity during dynamic movement.

These observations confirm that RF signal characteristics can be effectively correlated with UAV behavior. The system successfully distinguishes UAV communication from background noise and provides meaningful insights into operational states.

6. Validation

The system was validated through multiple experimental trials to ensure consistency and reliability. Repeated tests under identical conditions demonstrated stable RF signal detection and consistent feature extraction results.

Behavioral patterns observed during different flight phases remained consistent across multiple trials, confirming the robustness of the correlation process.

Interference testing in environments with moderate wireless activity showed that band-pass filtering effectively mitigates noise, ensuring accurate signal analysis. Long-duration monitoring tests confirmed system stability, with no data loss or processing interruptions.

7. Conclusion and Future Work

This paper presented a passive RF-based framework for the behavioral characterization of consumer-grade UAV control systems. The system successfully demonstrated that UAV communication behavior can be analyzed using low-cost hardware and signal processing techniques without requiring active transmission or interference.

The results indicate that passive RF sensing is a viable and scalable approach for UAV monitoring, offering advantages such as non-intrusive operation, independence from environmental conditions, and cost-effectiveness. The ability to correlate RF signal characteristics with UAV operational states provides deeper insights compared to traditional detection systems.

Future work may focus on integrating machine learning algorithms for automated classification of UAV behavior, expanding the system to multi-band monitoring, and incorporating multi-antenna setups for direction finding and localization.

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